Extraction of γ from charmless hadronic $B \to PP$ decays using SU(3) flavor symmetry

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Abstract. The decays of B mesons to a pair of charmless pseudoscalar mesons (PP decays) have been analyzed within the framework of flavor SU(3) symmetry and quark-diagrammatic topological approach. Flavor symmetry breaking is taken into account in tree (T) amplitudes through ratios of decay constants f_K and f_π; exact SU(3) is assumed elsewhere. Acceptable fits to $B \to PP$ branching ratios and CP asymmetries are obtained with tree, color-suppressed and QCD penguin amplitudes. Singlet penguin amplitude was introduced to describe decay amplitudes of the modes with η and η' mesons in the final state. Electroweak penguin amplitudes were expressed in terms of the corresponding tree-level diagrams. Values of the weak phase γ were found to be consistent with the current indirect bounds from other analyses of CKM parameters.

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The main idea behind the study of B meson decays is to get precise information on Cabibbo-Kobayashi-Maskawa (CKM) matrix elements. Testing the KM mechanism [1] of CP violation in flavor physics requires many measurements of branching ratios and CP-violating observables. To consistently compare different results on common ground it is convenient to express them in terms of constraints on the apex of the CKM triangle in the $\rho - \eta$ plane where ρ and η are parameters of the Wolfenstein parametrization of the CKM matrix. The weak phase $\beta \equiv \arg(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$ was measured in $b \to c\bar{c}s$ decays with high precision. Currently, this CKM angle is determined to lie within a 3.8° interval, $21.1^\circ \leq \beta \leq 24.9^\circ$, at 95% confidence level [2]. Until recently, only indirect constraints existed for the other two CKM angles, $\alpha \equiv \arg(-V_{td}V_{tb}^*/V_{ud}V_{ub}^*)$ and $\gamma \equiv \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$, with much larger allowed ranges: $82^\circ \leq \alpha \leq 115^\circ$ and $43^\circ \leq \gamma \leq 74^\circ$ at 95% confidence level. Now, we also have direct measurements of γ in charmed B decays, $\gamma = (68^{+14}_{-15} \pm 13 \pm 11)^\circ$ at 1σ level [3, 4], and direct measurements of α in $b \to u\bar{u}d$ transitions, $\alpha = (99^{+12}_{-9})^\circ$ at 1σ level [3].

Decays to two-body hadronic charmless final states are particularly useful since many of them involve more than one significant quark subprocess. Typically the weak phase difference between tree and penguin-type diagrams is equal to γ. When the strong phases are substantially different, too, a decay has the potential for displaying direct CP asymmetries which can be observed in experiment. A reliable extraction of γ is dependent on our ability to understand the pattern of strong phases in as wide as possible a set of decays. Final state interaction (FSI) strong phases involve non-perturbative long-distance physics and cannot be computed from first principles. A data-driven flavor topology approach based on the assumption of the SU(3) flavor symmetry [5, 6, 7] offers a way to extract FSI strong phases associated with individual topological amplitudes together with the weak phase γ and topological decay amplitudes.

In this analysis, we take flavor SU(3) symmetry [8, 9, 10, 11, 12] as a working hypothesis. Assuming factorization, we take account of SU(3) symmetry breaking effects due to decay constant differences only when relating strangeness-conserving and strange-changing tree amplitudes. We do not expect factorization to work in penguin and color-suppressed amplitudes so we don't make any specific assumptions beyond the strict SU(3) symmetry. The ratios of strangeness-conserving and strange-changing amplitudes for these two types of amplitudes are assumed to be completely determined by the ratio of the weak CKM matrix elements involved in either transition. From the results of fits to *PP* data one can extract information about fit parameters, compare with other known constraints, and make predictions for as-yet-unseen decay modes. The values of γ obtained in *PP* fits are consistent with the current indirect bounds [2].

Several important lessons were learned while searching for a good *PP* fit to the current data. First of all, a large relative strong phase $\delta_C \simeq -70^\circ$ between the color-suppressed C and tree T amplitudes is crucial for getting a satisfactory agreement between fit expectations and the experimental data. Another key point is the importance of a penguin amplitude P_{tu} associated with intermediate t and u quarks. When it is not explicitly taken into account as a fit parameter, it disguises itself as a part of the tree T and color-suppressed C amplitudes, interfering destructively with the former and constructively with the latter. When P_{tu} is added as a fit parameter, the updated fit to the most recent experimental data on $\pi\pi$, πK and KK decays separates P_{tu} and tree-level amplitudes to predict a more reasonable $|C/T| \simeq 0.5$ which is still larger than expected.

The values of both the $|C/T|$ amplitude ratio and the relative phase δ_C are roughly consistent with the result for the C/T ratio inferred from $D\pi$ decays [13, 14]. The extraction of this ratio from charmless *PP* decays yields a larger $|C/T|$ ratio and a larger phase than expected from the QCD factorization approach. This indicates that soft final-state interactions play an important role in B physics despite the naive expectation that products of energetic B decays move away too fast to experience final-state rescattering. Alternative explanations include electroweak penguins enhanced due to the presence of New Physics [15, 16].

We performed two versions of *PP* fits. One was a fit to all modes that do not contain η or η' in the final state (19 data points, 8 fit parameters). The other was the full *PP* fit (30 data points, 12 fit parameters, including two singlet penguin amplitudes, S' and S_{tu}, and their strong phases). Both versions of *PP* fits have a local χ^2 minimum in the range $43^\circ \leq \gamma \leq 74^\circ$ allowed by global fits to phases of the CKM matrix [2]: $\gamma = (43 \pm 12 \pm 2)^\circ$ in the smaller fit and $\gamma = (60 \pm 9 \pm 2)^\circ$ in the full fit.

The first uncertainty is statistical and data driven. We also did a rough estimate of the theoretical uncertainty related to the assumption of SU(3) symmetry. The same *PP* fits were performed once with the assumption of symmetry breaking in the ratio of decay constants (i.e. with $f_K/f_\pi \simeq 1.22$) and one more time under the assumption of strict SU(3), i.e. with f_K/f_π fixed to 1. Naturally, preferred parameter values shifted a little bit from their previous values but the deviations were very small (just 2° for the CKM phase γ). They are shown as second (theoretical) uncertainties. These uncertainties are much smaller than the corresponding statistical uncertainties for all fit parameters.

Thus, acceptable fits to *PP* branching ratios and *CP* asymmetries were obtained with tree, color-suppressed, penguin, and electroweak penguin amplitudes. The penguin amplitude P_{tu} associated with intermediate t and u quarks was found to considerably improve the quality of PP fits. Contrary to expectations, the value of relative strong phase δ_C between C and T amplitudes and the value of the $|C/T|$ ratio were found to be large, hinting at the presence of final-state interaction effects. So far, the data is accommodated reasonably well within the SM; the largest deviation from fit predictions does not exceed 1.8σ.

A joint SU(3) fit to all data on charmless hadronic B decays is currently being developed with the weak phase γ as a common parameter for the PP and VP sectors of the fit [7]. Just as in the case of separate PP and VP fits, one can extract the magnitudes and relative phases of different topological amplitudes and make predictions for rates and CP asymmetries in as-yet-unseen decay modes. Preliminary results of the VP fit are roughly consistent with those obtained in the analyses of $B \to PP$ decays. The global minimum of χ^2 is achieved at the weak phase $\gamma = (66.2 \pm 3.9 \pm 0.1)^\circ$. It favors γ within the range 62°–70° at the 1σ level, and 59°–73° at 95% confidence level.

A subgroup of SU(3) flavor symmetry, U-spin can also be applied to charmless B decays with the goal of γ extraction. In U-spin multiplet approach quark diagrammatic topologies are not employed at all. Unlike SU(3) based approach, in U-spin one does not need to make any assumptions about the relative sizes of various contributing topological diagrams and so no amplitude need be neglected. All formally small ($O(1/m_b)$) amplitudes such as exchange or annihilation diagrams are automatically fully contained within this approach. Preliminary results from U-spin fits to charged $B^\pm \to P^0 P^\pm$, $P^0 V^\pm$, $V^0 P^\pm$ and $V^0 V^\pm$ decays [17] yield $\gamma = (54^{+12}_{-11})^\circ$. This approach is currently being extended to include neutral B^0 decays, too [18].

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